Techno-Economic Evaluation of Deploying CO$_2$ Capture in an Integrated Steel Mill

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Total value of the Project: 4.4 million SKr
IEA GHG Contribution: 1.2 million SKr
Co-Authors of this Study

- Swerea MEFOS Team
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  - Karl Anders Hoff
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- IEA Greenhouse Gas R&D Programme
  - Stanley Santos
  - Steve Goldthorpe
Objectives of the Study

• To specify a “REFERENCE” steel mill typical to Western European configuration and evaluate the techno-economic performance of the integrated steel mill with and without CO₂ capture.

• To determine the techno-economic performance, CO₂ emissions and avoidance cost of the following cases:
  • An integrated steel mill typical to Western Europe as the base case.
  • An end of pipe CO₂ capture using conventional MEA at two different levels of CO₂ capture rate
  • An Oxygen Blast Furnace (OBF) and using MDEA for CO₂ capture.
Terminologies / Abbreviations

- **OBF**  Oxy-Blast Furnace
- **OBF-PG**  Oxy-Blast Furnace Process Gas
- **OBF-TG**  Oxy-Blast Furnace Top Gas
- **TGR**  Top Gas Recycle
- **BFG**  Blast Furnace Gas
- **BOFG**  Basic Oxygen Furnace Gas
- **COG**  Coke Oven Gas
- **SGP**  Steam Generation Plant
Integrated Steelmaking Process

- Raw Materials Preparation Plants
  - Coke Production
  - Ore Agglomerating Plant (Sinter Production)
  - Lime Production
- Ironmaking
  - Blast Furnace
  - Hot Metal Desulphurisation
- Steelmaking
  - Basic Oxygen Steelmaking (Primary)
  - Secondary Steelmaking (Ladle Metallurgy)
- Casting
  - Continuous Casting
- Finishing Mills
  - Hot Rolling Mills (Reheating & Rolling)
Extra-Ordinary Assumptions
(For European Scenarios)

- Only one type of steel product (standard grade HRC) produced and sold.
- Plant Ownership Structure not typical to European Steel Mill Scenario
  - Captive Ownership: Power Plant, ASU and Lime Plant
- Captive Power Plant with Balanced Electricity Supply to the Steel Mill.
- Captive Coke Plant with Balanced Supply of Coke to the Steel Mill.
- Direct emissions related to the Pellets and Merchant Scrap not included in overall CO\(_2\) emission accounting.
Direct CO₂ Emissions from the REFERENCE Steel Mill

- Nearly 95% of the total CO₂ Emissions from the Integrated Mill that produces 4 million tonnes of Hot Rolled Coil:
  - Power Plant (47.0%)
  - Ironmaking (21.2%)
  - Sinter Production (14.0%)
  - Coke Production (9.3%)
  - Lime Production (3.4%)
Key Messages from this Study

An Integrated Steel Mill is a complex industrial process which consists of Multiple Point Sources of CO₂ Emissions

<table>
<thead>
<tr>
<th>UNIT</th>
<th>Source of CO₂ Emissions</th>
<th>Emissions (kg/t HRC)</th>
<th>Annual Emission (t/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>Coke oven flue gas</td>
<td>191.37</td>
<td>765,495</td>
</tr>
<tr>
<td>100</td>
<td>Coke oven gas flare</td>
<td>3.30</td>
<td>13,196</td>
</tr>
<tr>
<td>200</td>
<td>Sinter plant flue gas (CO₂ + CO)</td>
<td>289.46</td>
<td>1,157,825</td>
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<tr>
<td>300</td>
<td>Hot Stove flue gas</td>
<td>415.19</td>
<td>1,660,769</td>
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<tr>
<td>400/1300</td>
<td>PCI Coal drying, torpedo car and ladle heating (HM Desulphurisation) diffuse emissions</td>
<td>7.76</td>
<td>31,042</td>
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<tr>
<td>300</td>
<td>Blast Furnace Gas flare</td>
<td>19.73</td>
<td>78,931</td>
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<tr>
<td>500/600</td>
<td>Basic Oxygen Furnace gas flared and system losses, SM diffuse Emissions</td>
<td>51.02</td>
<td>204,089</td>
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<tr>
<td>700</td>
<td>Continuous Casting - diffuse emissions (from slab cutting)</td>
<td>0.80</td>
<td>3,188</td>
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<tr>
<td>800</td>
<td>Reheating Furnace flue gas</td>
<td>57.71</td>
<td>230,833</td>
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<tr>
<td>900</td>
<td>Hot Rolling Mills - diffuse emissions (from cutting and scarfing)</td>
<td>0.04</td>
<td>179</td>
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<tr>
<td>1000</td>
<td>Lime Plant flue gas</td>
<td>71.62</td>
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<tr>
<td>1200</td>
<td>Power Plant flue gas</td>
<td>982.13</td>
<td>3,928,513</td>
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<tr>
<td>1300</td>
<td>Ancillaries transport fuel emissions (trucks and rails)</td>
<td>4.00</td>
<td>16,000</td>
</tr>
<tr>
<td></td>
<td><strong>Total Emissions</strong></td>
<td><strong>2094.14</strong></td>
<td><strong>8,376,554</strong></td>
</tr>
</tbody>
</table>
Key Messages from this Study

An Integrated Steel Mill is a complex industrial process which consists of Multiple Point Sources of CO₂ Emissions

Ironmaking Process is responsible for nearly 80% of the Carbon Input that causes the majority of the Direct CO₂ Emissions (i.e. 1640 out of 2090 kg CO₂ / t HRC) of the Integrated Steel Mill
Nitrogen
2 Nm³

Raw Materials
Coke 355 kg
Sinter 1120 kg (70%)
Pellets 352 kg (22%)
Lump 125 kg (8%)
Limestone 13 kg
Quartzite 11 kg

BF Screen
Undersize
23 kg

Top Gas Cleaning

BFG Gas Holder

BFG to Power Plant
935 Nm³
BFG to Coke Plant
185 Nm³
BFG to Hot Stoves
479 Nm³

COG
7 Nm³
Air
358 Nm³

Flue Gas
780 Nm³

BFG to Flare/Lost
23 Nm³

All Values are reported as kg or Nm³ per tonne of hot metal (thm)
Carbon Balance of Ironmaking Process

Direct CO₂ Emissions of an Integrated Steel Mill (REFERENCE) Producing 4 MTPY Hot Rolled Coil
2090 kg CO₂/t HRC (2107 kg CO₂/thm)

Carbon Input
(kg C/thm)

Coke 312.4
Limestone 1.5
PCI Coal 132.2
COG 1.3
Total 447.5

Carbon Output
(kg C/thm)

Hot Metal 47.0
BF Screen Undersize 6.3
Dust & Sludge 8.0
BFG Export 266.4
BFG Flared 5.4
Hot Stove’s Flue Gas 114.1
Total 447.2

For this case study, it was demonstrated that the ironmaking process is responsible for 78% of the total carbon input of the steel mill. BUT only 21% of the carbon emitted as CO₂ emissions is attributed to this process. The rest of the carbon emitted as CO₂ are accounted to other processes (mostly end users of the by-product fuel gases) within the steel mill.
Carbon Balance of Ironmaking Process

Direct CO₂ Emissions of an Integrated Steel Mill (REFERENCE)
Producing 4 MTPY Hot Rolled Coil
2090 kg CO₂/t HRC (2107 kg CO₂/thm)

Carbon Balance of Ironmaking Process

<table>
<thead>
<tr>
<th>Carbon Input (kg C/thm)</th>
<th>Carbon Output (kg C/thm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coke</td>
<td>312.4</td>
</tr>
<tr>
<td>Limestone</td>
<td>1.5</td>
</tr>
<tr>
<td>PCI Coal</td>
<td>132.2</td>
</tr>
<tr>
<td>COG</td>
<td>1.3</td>
</tr>
<tr>
<td>Total</td>
<td>447.5</td>
</tr>
</tbody>
</table>

For this case study, it was demonstrated that the ironmaking process is responsible for 78% of the total carbon input of the steel mill. BUT only 21% of the carbon emitted as CO₂ emissions is attributed to this process. The rest of the carbon emitted as CO₂ are accounted to other processes (mostly end users of the by-product fuel gases) within the steel mill.
# STEEL MILL Battery Limit

(REFERENCE Integrated Steel Mill)

<table>
<thead>
<tr>
<th>Unit 100:</th>
<th>Unit 200:</th>
<th>Unit 300:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coke Production</td>
<td>Sinter Production</td>
<td>Hot Metal Production</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Unit 400:</th>
<th>Unit 500:</th>
<th>Unit 600:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Metal Desulphurisation</td>
<td>Basic Oxygen Steelmaking</td>
<td>Secondary Steelmaking</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Unit 700:</th>
<th>Unit 800:</th>
<th>Unit 900:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous Slab Casting</td>
<td>Slab Reheating</td>
<td>Hot Rolling Mill</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Unit 1000:</th>
<th>Unit 1100:</th>
<th>Unit 1200:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lime Production</td>
<td>Air Separation Unit (Oxygen Production)</td>
<td>Power Plant</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Unit 1300:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ancillary Units</td>
</tr>
</tbody>
</table>
STEEL MILL Battery Limit
(Steel Mill with OBF & MDEA CO₂ Capture)
Integrated Steel Mill with OBF and MDEA CO$_2$ Capture Technology

Changes to the Steel Mill as compared to the REFERENCE Steel Mill (Base Case)
Materials Input & Output

- Major Raw Materials Input:
  - Iron Burden (Fines, Lumps, Pellets)
  - Energy and Reductant
    - Coking Coal
    - PCI Coal
    - Natural Gas
  - Fluxes (Limestone, Quartzite, Olivine, CaC₂, Burnt Dolomite) Merchant Scrap (External)
  - Ferroalloys (FeMnC, FeSi-75, De-Ox Aluminium)

- Major Intermediate Products
  - Coke (Lump & Breeze)
  - Sinter
  - Hot Metal
  - Liquid Steel
  - Slab
  - Lime
  - HP & LP Oxygen
  - Electricity
  - Steam

- Products and By-Products:
  - Hot Rolled Coil (Standard Grade)
  - Coking Plant By-Products
    - Crude Tar, BTX and Sulphur
  - Steel Mill Slag
    - Granulated BF Slag (Sale)
    - De-S Slag (Landfill)
    - BOF Slag (Sale & Landfill)
    - SM Slag (Landfill)
  - BF Sludge and Dust (Landfill)
  - MDEA Sludge (Landfill)
  - Liquid Argon

- Gas Network within Site
  - Industrial Gases
    - HP & LP Oxygen, Nitrogen and Argon
  - Off-Gases
    - OBF Top Gas
    - OBF Process Gas (PG)
    - Coke Oven Gas (COG)
    - Basic Oxygen Furnace Gas (BOFG)
  - Steam (9 Bar, saturated)
  - Carbon Dioxide
Material Process Flow Diagram
(Steel Mill with OBF/MDEA CO₂ Capture)

- **Installation of Oxy-Blast Furnace**
  - Reduced coke consumption
  - Reduced flux consumption
  - Reduced GBF slag production

- **Reduce Coke Plant Capacity**
  - Reduced coking coal consumption
  - Reduced by-products production to sale

- **Changes in Sinter Plant**
  - Reduced sinter’s CaO/SiO₂ ratio from 1.80 to 1.65
  - Reduced flux consumption

- **Reduced in Flux Consumption**
  - Limestone, Quartzite (OBF / Sinter)
  - Lime, Olivine (Sinter)

- **Addition of CO₂ capture plant**
  - handling of Make Up MDEA/Pz solvent and disposal of MDEA sludge

Legend
- Mill Scales
- Reheating & HRM
- Coke Plant
- Steel Making
- Iron Making
- Sinter Plant
- Lime Plant
- BF Slag
- BF Dust & Sludge
- MDEA Sludge
- CO₂ Capture Plant
- Metal Slack
- Slag (250°C)
- Slag (350°C)
- Slag (500°C)
- BF Sludge
- BOS Slag
- Hard Coking Coal
- Soft Coking Coal
- Lump Coke
- PCI Coal
- FerroAlloy
- Al
- Sinter Fines (Sweden)
- BF/BOS Dust & Sludge
- Reclaimed Coke (ex BF screen)
- BF Screen Undersize (excl. coke)
- Sinter Fines (Australia)
- Sinter Fines (Brazil)
- Limestone
- Quartzite
- Lime
- Calcium Carbide
- Burnt Dolomite
- Coke
- Coke Breeze
- BF Pellets
- Dry Sludge
- Liquid Steel (99% Fe)
- Slab Caster
- Slab (100°C)
- Mill Scales
- Scrap
- Reheating & HRM
- UNIT 100
- UNIT 200
- UNIT 300
- UNIT 400
- UNIT 500
- UNIT 600
- UNIT 700
- UNIT 800
- UNIT 900
- UNIT 1000
- UNIT 2000
- UNIT 3000
- UNIT 4000
- UNIT 5000
Gas Network - Process Flow Diagram
(Steel Mill with OBF/MDEA CO₂ Capture)

• Installation of Oxy-Blast Furnace
  • Added the Recycling of Top Gas with CO₂ removal.
  • Delivery of Top Gas to the CO₂ Capture and Compression Plant
  • Introduction of OBF Process Gas (OBF PG - Recycled Top Gas after CO₂ removal) to shaft and tuyeres.
  • Reduced Off-Gas from BF as fuel for Plant Use.
  • Five folds increase to the consumption of Oxygen for the blast furnace
    • Only requires 95% purity O₂
    • Oxygen is introduced to the OBF at the tuyeres level without pre-heating (cold).

• Replacement of Hot Stoves with Fired Heaters
  • Purpose: to heat up the OBF-PG delivered to the shaft level up to 900°C

• Reduced COG consumption –
  • NG is used as fuel for the Fired Heaters.

• Increased COG consumption by the PCI Coal Drying Units.

• No BFG Flaring (significantly minimise to nearly zero)
Gas Network - Process Flow Diagram
(Steel Mill with OBF/MDEA CO₂ Capture)

- Installation of ASU with Low Purity O₂ production to meet OBF demand.
  - Reduced the capacity of ASU – High Purity O₂ Production by ~43%.
  - Reduced Liquid Argon to Sale

- Reduce Coke Plant Capacity
  - Reduced COG supply to the steel mill
  - Modification to coke oven’s underfire heating fuel demand & composition.
    - Reduced Fuel demand
    - Reduced COG consumption
    - Replacement of BFG by OBF-PG
  - Flaring should be nearly zero to meet COG demand

- Addition of CO₂ capture plant
  - Requires processing of OBF Top Gas prior to CO₂ capture.
  - Delivery of the OBF Process Gas to OBF and other Plant Users
  - Requires low pressure steam for solvent regeneration
Gas Network - Process Flow Diagram
(Steel Mill with OBF/MDEA CO2 Capture)

- Steam supplied by the Waste Heat Boilers of the Basic Oxygen Furnace
  - Supply steam to meet demand of:
    - Coke Plant
    - ASU – HP O2 Production
    - ASU – LP O2 Production
    - No steam demand by the OBF
  - Maximise the steam production from the Waste Heat Boilers installed at the Basic Oxygen Furnace and deliver excess steam to CO2 capture plant.

- Installation of Low Pressure Steam Generation Plant to meet CO2 Capture Plant demand.
  - Used OBF-PG and BOFG as the main fuel and with NG as supplementary fuel to meet demand of the boilers.
Electricity Network of the Integrated Steel Mill
(Steel Mill with OBF/MDEA CO2 Capture)

**Captive Power Plant**

<table>
<thead>
<tr>
<th>REF. Steel Mill</th>
<th>OBF Steel Mill w/ CO2 Capture</th>
</tr>
</thead>
<tbody>
<tr>
<td>215 MWe (Net)</td>
<td>292 MWe (Net)</td>
</tr>
<tr>
<td>32.1%</td>
<td>56.9%</td>
</tr>
<tr>
<td>BFG, BOFG, NG</td>
<td>NG</td>
</tr>
<tr>
<td>400 kWh/t HRC</td>
<td>573 kWh/t HRC</td>
</tr>
<tr>
<td>85% Load Factor</td>
<td>89% Load Factor</td>
</tr>
<tr>
<td>Gas Fired Boiler</td>
<td>NGCC Single Shaft</td>
</tr>
</tbody>
</table>

**Scope for Improvements:**
- Deployment of CHP or COGEN Plant instead of Steam Boilers to generate steam for CO2 capture plant
- To evaluate other possible waste heat recovery within the steel mill for steam generation.
- BUT – this may not be possible for several European Steel Mills as they provide district heating.
Oxy-Blast Furnace Operation
(Picture of OBF courtesy of Tata Steel)

Raw Materials
- Coke 253 kg
- Sinter 1096 kg (70%)
- Pellets 353 kg (22%)
- Lump 125 kg (8%)
- Limestone 6 kg
- Quartzite 3 kg

OBF Screen
- Undersize 21 kg

OBF Process Gas
- Flue Gas 352 Nm³
- BF Sludge 4 kg
- Steam 2.0 GJ

OBF Top Gas
- CO₂ Capture & Compression Plant
- Carbon Dioxide 867 kg

OBF Process Gas Fired Heaters
- Natural Gas
- Air
- Oxygen 253 Nm³
- Nitrogen 5 Nm³
- PCI Coal 152 kg

Oxygen 253 Nm³
Nitrogen 5 Nm³

Carbon Dioxide 867 kg

OBF-PG to Steel Works
- Hot Metal 1000 kg 1470°C
- PCI Coal 152 kg
- Oxygen 253 Nm³
- Nitrogen 5 Nm³

OBF Process Gas
563 Nm³ 900°C
205 Nm³ 410°C

OBF Top Gas
1385 Nm³
BF Dust 15 kg
BF Sludge 4 kg

Top Gas Cleaning

Oxy-Blast Furnace Operation
(Picture of OBF courtesy of Tata Steel)
Carbon Balance of Ironmaking Process
(Equipped with OBF and MDEA/Pz CO₂ Capture)

Direct CO₂ Emissions of an Integrated Steel Mill (with OBF & MDEA CO₂ Capture) Producing 4 MTPY Hot Rolled Coil
1115 kg CO₂/t HRC (1124 kg CO₂/thm)

For this case study, the Oxy-Blast Furnace has the potential to reduce carbon input to the iron making process by 17% as compared to the REFERENCE case (@447.5 kg C/thm). This is due to the reduced consumption of the coke. ULCOS has reported a higher carbon input reduction potential of up to ~28%. Further reduction of CO₂ emissions could only be achieved by CCS.
Note:

- Current study only illustrates one of the many options available for oxy-blast furnaces

- This do not represents the choice made by the ULCOS Programme.
  - Florange Project
  - Eisenhüttenstadt Project
The Ulcos Blast Furnace Concepts

Coke

Top gas (CO, CO₂, H₂, N₂)

Gas cleaning

Gas net (N₂ purge)

CO₂ scrubber

CO₂ 400 Nm³/t

CO, H₂, N₂

Gas heater

CO, H₂, N₂

V4 900 °C

V3 1250 °C

V1 900 °C

Oxygen

PCI

Re-injection

Expected C-savings

25 %

24 %

21 %
CO₂ Capture & Compression Plant PFD
(Steel Mill – OBF and MDEA CO₂ Capture)
CO₂ Capture & Compression Plant PFD
(Steel Mill – OBF and MDEA CO₂ Capture)

• Equipment Configuration:
  • 2x Process Gas Compressors (2 to 4 Barₐ)
  • 2x Absorbers (1 per OBF)
  • 1x Stripper Column
  • 2x CO₂ Compression Train with Glycol (TEG) Dehydration Unit

• Solvent
  • MDEA 40%
  • Piperazine 10%

• Energy Demand
  • Steam 2.02 GJ/t HRC
  • Electricity 143.2 kWh/t HRC

• Capture Performance
  • ~860 kg/t HRC (867 kg/thm)
  • ~47% CO₂ Avoided
  • 94% capture rate
Separation and Capture of CO$_2$ from OBF also has several other options (Data from ULCOS Programme)

- PSA, VPSA
- VPSA + Cryogenics
- Separation of non-CO$_2$ components
- Chemical Absorption

<table>
<thead>
<tr>
<th>Table C-1: Comparison of CO$_2$ Capture Technologies for an Integrated Steel Mill (BF-BOF Route) ULCOS Project Evaluation Results [2, 4]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Recycled Top Gas (Process Gas)</td>
</tr>
<tr>
<td>CO$_2$ vol %</td>
</tr>
<tr>
<td>Process Gas Composition</td>
</tr>
<tr>
<td>CO$_2$ vol %</td>
</tr>
<tr>
<td>CO vol %</td>
</tr>
<tr>
<td>H$_2$ vol %</td>
</tr>
<tr>
<td>N$_2$ vol %</td>
</tr>
<tr>
<td>H$_2$O vol %</td>
</tr>
<tr>
<td>Captured CO$_2$ Rich Gas</td>
</tr>
<tr>
<td>CO$_2$ vol %</td>
</tr>
<tr>
<td>CO vol %</td>
</tr>
<tr>
<td>H$_2$ vol %</td>
</tr>
<tr>
<td>N$_2$ vol %</td>
</tr>
<tr>
<td>Suitable for CO$_2$ Transport &amp; Storage?</td>
</tr>
<tr>
<td>Electricity Consumption</td>
</tr>
<tr>
<td>Capture Process kWh/t CO$_2$</td>
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<tr>
<td>CO$_2$ Compression (110 bar$_g$) kWh/t CO$_2$</td>
</tr>
<tr>
<td>LP Steam Consumption GJ/t CO$_2$</td>
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<tr>
<td>Total Energy Consumption GJ/t CO$_2$</td>
</tr>
</tbody>
</table>
Techno-Economic Model
(Steel Mill with OBF & MDEA CO2 Capture)
# Total Investment Cost
(REFERENCE vs. OBF/MDEA Case)

<table>
<thead>
<tr>
<th>Unit No.</th>
<th>Plant Section</th>
<th>REFERENCE Steel Mill</th>
<th>Steel Mill with OBF / MDEA CO₂ Capture</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>Coke Production</td>
<td>400</td>
<td>310</td>
</tr>
<tr>
<td>200</td>
<td>Sinter Production</td>
<td>220</td>
<td>220</td>
</tr>
<tr>
<td>300 &amp; 400</td>
<td>Blast Furnace and Hot Metal Desulphurisation</td>
<td>622</td>
<td>610</td>
</tr>
<tr>
<td>500 &amp; 600</td>
<td>Basic Oxygen Steelmaking and Ladle Metallurgy</td>
<td>459</td>
<td>459</td>
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<tr>
<td>700</td>
<td>Continuous Slab Caster</td>
<td>195</td>
<td>195</td>
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<tr>
<td>800 &amp; 900</td>
<td>Reheating Furnace &amp; Hot Rolling Mills</td>
<td>450</td>
<td>450</td>
</tr>
<tr>
<td>1000</td>
<td>Lime Production</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>1100</td>
<td>ASU – High Purity O₂ Production</td>
<td>130</td>
<td>94</td>
</tr>
<tr>
<td>1200</td>
<td>Power Plant</td>
<td>280</td>
<td>362</td>
</tr>
<tr>
<td>2000</td>
<td>Steam Generation Plant</td>
<td>-</td>
<td>90</td>
</tr>
<tr>
<td>3000</td>
<td>ASU – Low Purity O₂ Production</td>
<td>-</td>
<td>134</td>
</tr>
<tr>
<td></td>
<td><strong>Plant and Equipment – Material Handling &amp; Spare Parts</strong></td>
<td>244</td>
<td>242</td>
</tr>
<tr>
<td></td>
<td>Raw Material Handling</td>
<td>128</td>
<td>128</td>
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<tr>
<td></td>
<td>Spare Parts and First Fill</td>
<td>116</td>
<td>114</td>
</tr>
<tr>
<td></td>
<td><strong>Plant and Equipment – Auxiliary, Utilities and BOP</strong></td>
<td>350</td>
<td>350</td>
</tr>
</tbody>
</table>

Total Investment Cost:
- REFERENCE: $2,772
- Steel Mill with OBF/MDEA CO₂ Capture: $2,940
## Total Investment Cost - Cont’d

(REFERENCE vs. OBF/MDEA Case)

<table>
<thead>
<tr>
<th>Unit No.</th>
<th>Plant Section</th>
<th>REFERENCE Steel Mill</th>
<th>Steel Mill with OBF / MDEA CO₂ Capture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Site Development, Construction and Project Engineering</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pre-operating Expenses</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Land Preparation, Site Development &amp; Waste Disposal</td>
<td>144</td>
<td>144</td>
</tr>
<tr>
<td></td>
<td>Buildings and Site Infrastructure</td>
<td>196</td>
<td>196</td>
</tr>
<tr>
<td></td>
<td>Project Engineering</td>
<td>201</td>
<td>201</td>
</tr>
<tr>
<td><strong>Total Installed Cost - Steel Mill (US$ Million)</strong></td>
<td></td>
<td>3,928</td>
<td>4,094</td>
</tr>
<tr>
<td><strong>Contingency @ 5% of Total Installed Cost - Steel Mill</strong></td>
<td></td>
<td>196</td>
<td>205</td>
</tr>
<tr>
<td><strong>CO₂ Capture and Compression Plant</strong></td>
<td></td>
<td></td>
<td>578</td>
</tr>
<tr>
<td>4000</td>
<td>Plant &amp; Equipment, First Fill, Spare Parts, BOP, Site Dev. Contingency (15% of Installed Cost – CO₂ Capture Plant)</td>
<td>-</td>
<td>503</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-</td>
<td>75</td>
</tr>
<tr>
<td><strong>Total Investment Cost – excl. Recurring CAPEX (US$ Million)</strong></td>
<td></td>
<td>4,124</td>
<td>4,877</td>
</tr>
<tr>
<td><strong>Recurring CAPEX (Blast Furnace Reline – Every 15th Year)</strong></td>
<td></td>
<td>232</td>
<td>232</td>
</tr>
<tr>
<td><strong>Specific Investment Cost – excl. Recurring CAPEX (US$ / t HRC)</strong></td>
<td></td>
<td>1,031</td>
<td>1,219</td>
</tr>
</tbody>
</table>
## Annual O&M Cost

(REFERENCE vs. OBF/MDEA Case)

<table>
<thead>
<tr>
<th>Cost Items</th>
<th>Reference Steel Mill</th>
<th>OPEX (US$ Million/y)</th>
<th>Steel Mill with OBF / MDEA CO₂ Capture</th>
<th>OPEX (US$ Million/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fixed O&amp;M Cost</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual Maintenance Cost</td>
<td>141,996</td>
<td>422,717</td>
<td>163,633</td>
<td>445,294</td>
</tr>
<tr>
<td>Direct Labour Cost</td>
<td>204,581</td>
<td></td>
<td>205,521</td>
<td></td>
</tr>
<tr>
<td>Indirect Labour Cost</td>
<td>76,140</td>
<td></td>
<td>76,140</td>
<td></td>
</tr>
<tr>
<td><strong>Variable O&amp;M Cost</strong></td>
<td>1288,650</td>
<td></td>
<td>1369,904</td>
<td></td>
</tr>
<tr>
<td>Fuel and Reductant</td>
<td>483,088</td>
<td></td>
<td>562,214</td>
<td></td>
</tr>
<tr>
<td>Iron Ore (Fines, Lumps and Pellets)</td>
<td>492,054</td>
<td></td>
<td>492,291</td>
<td></td>
</tr>
<tr>
<td>Purchased Scrap and Ferroalloys</td>
<td>218,228</td>
<td></td>
<td>218,228</td>
<td></td>
</tr>
<tr>
<td>Fluxes</td>
<td>44,650</td>
<td></td>
<td>40,091</td>
<td></td>
</tr>
<tr>
<td>Consumables &amp; Other Utilities</td>
<td>49,781</td>
<td></td>
<td>57,080</td>
<td></td>
</tr>
<tr>
<td><strong>Other Works Expense and Service Charges</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miscellaneous Works Expense</td>
<td>50,398</td>
<td></td>
<td>48,066</td>
<td></td>
</tr>
<tr>
<td>Other Misc. OPEX (including environmental clean up)</td>
<td>11,240</td>
<td></td>
<td>10,070</td>
<td></td>
</tr>
<tr>
<td><strong>Other O&amp;M Cost</strong></td>
<td>8,181</td>
<td></td>
<td>8,602</td>
<td></td>
</tr>
<tr>
<td>Slag Processing</td>
<td>3,578</td>
<td></td>
<td>3,568</td>
<td></td>
</tr>
<tr>
<td>On-Site Haulage</td>
<td>0,268</td>
<td></td>
<td>0,265</td>
<td></td>
</tr>
<tr>
<td>Disposal and Landfill</td>
<td>4,335</td>
<td></td>
<td>4,769</td>
<td></td>
</tr>
</tbody>
</table>

**Annual O&M Cost (US$ Million/y)**

**REFERENCE Steel Mill**: 1,781,795

**Steel Mill with OBF / MDEA CO₂ Capture**: 1,882,835
# Revenues from By-Products

(REFERENCE vs. OBF/MDEA Case)

<table>
<thead>
<tr>
<th>Cost Items</th>
<th>REFERENCE Steel Mill</th>
<th>Steel Mill with OBF / MDEA CO₂ Capture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sales Breakdown</td>
<td>Annual Sales (US$ Million/y)</td>
</tr>
<tr>
<td>Coke By-Products</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crude Tar</td>
<td>11.806</td>
<td>21.423</td>
</tr>
<tr>
<td>Benzole</td>
<td>9.197</td>
<td></td>
</tr>
<tr>
<td>Sulphur</td>
<td>0.420</td>
<td></td>
</tr>
<tr>
<td>Steel Mill Slags</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Granulated BF Slag</td>
<td>17.780</td>
<td>18.230</td>
</tr>
<tr>
<td>ROS Slag</td>
<td>0.450</td>
<td></td>
</tr>
<tr>
<td>Liquid Argon</td>
<td></td>
<td>14.018</td>
</tr>
</tbody>
</table>

**Annual Sale Revenue – By Products (US$ Million/y)**

- **REFERENCE Steel Mill**: 53.670
- **Steel Mill with OBF / MDEA CO₂ Capture**: 34.959
Cost of Steel Production – Breakdown

Breakeven Price of $575.23

- Capital Cost: $135
- Fuel & Reductant: $118
- Iron Ore (Fines, Lumps & Pellets): $120
- Purchased Scrap & FerroAlloys: $53
- Fluxes: $11
- Other Raw Mat'l & Consummables: $12
- Labour: $70
- Maintenance & Other O&M: $55

55% of the Cost is related to Raw Materials, Energy and Reductant.
Increase in CAPEX and Fuel Cost due to the addition of the CO2 capture facilities represents a $47 increase in the breakeven price of HRC.
Impact of the OBF/MDEA CO\textsubscript{2} Capture Plant to the Breakeven Cost of HRC Production

(Very Specific to this Study)

- Capital Cost increased by 18.8%
- Fuel and Reductant Cost increased by 17.3%
  - Coking Coal Cost – decreased by \sim 24%
  - Natural Gas Cost – increased by \sim 495%
- Iron Burden Cost increased by 1.0%
  - Iron Ore (Fines, Lumps and Pellets), Purchased Scrap & Ferroalloys
- Fluxes Cost decreased by 9.4%
  - Significant reduction of limestone and quartzite consumption
- Other Consumable Cost increased by 15.7%
  - Increased in cost of raw water consumption
  - Additional cost due to Chemicals & Consumables used by SGP.
  - Additional cost due to MDEA/Pz Solvent Make Up
- Labour Cost increased by 1.4%
- Maintenance and Other OPEX increased by 10.4%
<table>
<thead>
<tr>
<th>Key Messages from this Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>To incorporate OBF and CO\textsubscript{2} Capture in an Integrated Steel Mill producing 4 million tonnes of HRC per year would require an additional $753 million in CAPEX based on <strong>New Build Steel Mill Analysis</strong>.</td>
</tr>
<tr>
<td>In terms of OPEX – the steel mill with OBF and MDEA CO\textsubscript{2} Capture would require an additional <strong>US$ 120 Million per year</strong>.</td>
</tr>
<tr>
<td>This estimates is based on pre-feasibility level – having a defined +/-30% accuracy - and are based on conservative assumptions.</td>
</tr>
</tbody>
</table>
Evolution of Coking Coal Price
(Data provided by P. Baruya – IEA CCC)

Source: McCloskey (2011); ABARES (2011a).
Summary of Results
(Sensitivity to Coke Price)

It should be noted that Steel Mill used a significant variety of coking coal depending on market price (low to high quality coking coal)

COKE is a tradable commodity

CO2 Avoidance Cost = ~$56.4/t

+ $92/t Coke
Important Note

• The OBF and MDEA CO₂ Capture CAN NOT be classified as Post- or Oxy- or Pre- Combustion CO₂ Capture Technologies.
  • Blast furnace is a reduction process (not combustion!)
  • Separation of the CO₂ from the top gas is more analogous to the removal of CO₂ during the processing of natural gas.
  • Raw Top Gas from OBF is mainly CO (46%) and CO₂ (34%)
## Composition of OBF Top Gas, Process Gas, BOFG and COG.

<table>
<thead>
<tr>
<th>Wet Basis (%vol.)</th>
<th>Basic Oxygen Furnace Gas (BOFG)</th>
<th>OBF Top Gas (OBF-TG) to CO2 Capture Plant</th>
<th>OBF Process Gas (OBF-PG) from CO2 Capture Plant Recycled to BF</th>
<th>Wet Basis (%vol.)</th>
<th>Coke Oven Gas COG</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$</td>
<td>2.64</td>
<td>8.56</td>
<td>12.64</td>
<td>CH$_4$</td>
<td>23.04</td>
</tr>
<tr>
<td>CO</td>
<td>56.92</td>
<td>45.69</td>
<td>67.46</td>
<td>H$_2$</td>
<td>59.53</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>14.44</td>
<td>33.89</td>
<td>3.00</td>
<td>CO</td>
<td>3.84</td>
</tr>
<tr>
<td>N$_2$</td>
<td>13.83</td>
<td>10.07</td>
<td>14.86</td>
<td>CO$_2$</td>
<td>0.96</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>12.16</td>
<td>1.79</td>
<td>2.04</td>
<td>N$_2$</td>
<td>5.76</td>
</tr>
<tr>
<td>LHV (MJ/Nm$^3$) - wet</td>
<td>7.47</td>
<td>6.69</td>
<td>9.87</td>
<td>O$_2$</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>H$_2$O</td>
<td>3.98</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Other HC</td>
<td>2.69</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>LHV (MJ/Nm$^3$) - wet</td>
<td>17.33</td>
</tr>
</tbody>
</table>
Concluding Remarks

- Steel Mill with OBF/MDEA CO$_2$ Capture producing 4 MTPY standard Hot Rolled Coil was defined in detail in the study.
  - Mass Balance
  - Gas Network
  - Electricity Network
  - CO$_2$ emissions of each unit

- Study was able to established a baseline cost for an Integrated Steel Mill equipped with OBF, Top Gas Recycle and MDEA/Pz CO$_2$ capture technology.
Concluding Remarks

• Techno-Economics of Iron and Steel Production is very site specific.
  • Strategy for CCS Implementation to an integrated steel mill is also very site specific.

• **IMPORTANT to have a like for like assessment between steel mills without and with CO₂ capture.**

• Re-emphasized that this study is not meant to develop and evaluate the best available technology for the steel mill and CO₂ capture.

• One of the main objectives of this study is to establish a Techno-Economic Evaluation Methodology (Transparent) that could be used to estimate cost of CO₂ capture in an integrated steel mill on a like for like basis.
Concluding Remarks

• This study only touches the surface...

• REFERENCE Steel Mill is based on Typical Average European Configuration.
  • It should be expected that there will be inefficiency in some aspects of the steel mill.
  • To maintain a like for like analysis – the CO$_2$ capture configuration can’t include all the Best Available Technology as expected for Greenfield Steel Works. (For Example – Steam Generation Plant)
Key Message from this Study

- Key to the deployment of CO₂ capture technologies using top gas recycle to a blast furnace should also maximise the reduction in the coke consumption to make it cost competitive.

- Post-Combustion CO₂ Capture – i.e. capture of CO₂ from the flue gas of different stacks within the integrated steel mill - is not a cost competitive option!
  - This is not the options considered by the global steel community.

- REPORTING CO₂ Avoidance Cost for a complex industrial processes is meaningless – without establishing the assumptions used for the REFERENCE Plant without CO₂ Capture.
  - This is not a good indicator for these cases yet we are trapped in it...
Thank You

Stanley Santos
IEA Greenhouse Gas R&D Programme

stanley.santos@ieagghg.org
Back Up Slide
Key Price Inputs

- Price inputs for externally and internally sourced raw materials are based on actual operating price data adjusted to long term trends.
- Major intermediate products are priced based on the gate of the specific operating unit ("Factory").
- Revenues from sale of by-products is credited to the source of this materials.
- Details of these inputs are presented in the excerpt of the Volume 1 Report.
Notes on Investment Cost

• The integrated steel mill is assumed to have an economic life of 25 years as the basis for appraisal.

• The cost evaluation was developed in US$ (2010). Where necessary, the conversion was based on the following exchange rates:
  • € 1.00 = US$ 1.34
  • £ 1.00 = US$ 1.55

• The estimate accuracy is within the range +/- 30%.